

SMA¹ OBSERVATIONS OF GOODS 850-11 AND GOODS 850-13 — FIRST EXAMPLES OF MULTIPLE SUBMILLIMETER SOURCES RESOLVED BY AN INTERFEROMETER

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ABSTRACT

We carried out extremely sensitive Submillimeter Array (SMA) 340 GHz continuum imaging on two submillimeter galaxies (SMGs): GOODS 850-11 and GOODS 850-13. The observations reach sub-mJy rms sensitivities and, interestingly, resolve both sources into multiple, physically unrelated SMGs. GOODS 850-11 is resolved into two sources at different redshifts. GOODS 850-13 is resolved into three sources, two with different spectroscopic redshifts and one only with a photometric redshift. All the SMA sources have fluxes in the 3–5 mJy range and all are detected at 1.4 GHz. Three of them are detected by *Chandra*, and one is a previously unknown X-ray SMG. This is the first time that single-dish SMGs are resolved into multiple unrelated sources and also the first time that the SMA has discovered new SMGs. Our results show that identifications of SMGs at any wavelengths other than the submillimeter itself can be misleading, since such identifications usually only pick up one of the real counterparts. Using simulations that mimic our SCUBA and SMA observations, we find that the number of triple systems detected in our SMA survey is much higher than that expected from the current best-determined number counts. We tentatively attribute this to clustering. We also predict that ALMA will find $\sim 1/3$ of > 5 mJy 850 μ m SCUBA sources to be multiple systems. Based on our SMA observations and simulations, we suggest that large samples of existing SMGs should be imaged with sensitive interferometric observations, even if the SMGs were previously thought to be securely identified.

Subject headings: cosmology: observations — galaxies: evolution — galaxies: formation — galaxies: high-redshift — radio continuum: galaxies — submillimeter: galaxies

1. INTRODUCTION

Since the first discoveries of distant submillimeter galaxies (SMGs; Smail, Ivison, & Blain 1997; Barger et al. 1998; Hughes et al. 1998; Eales et al. 1999), tremendous progress has been made in understanding their nature and their role in galaxy evolution. With single-dish submillimeter surveys, we are now able to resolve approximately 30% of the 850 μ m background into point sources with $S_{850 \mu\text{m}} \gtrsim 2$ mJy and constrain their number counts fairly well at this bright end (e.g., Coppin et al. 2006). However, the low resolution of single-dish telescopes and the associated large positional uncertainties make the identification and followup of these sources quite difficult. Roughly 60%–70% of bright SMGs have counterparts in deep radio interferometric images (Barger, Cowie, & Richards 2000; Ivison et al. 2002; Chapman et al. 2003b) and their positions are known with subarcsec accuracy. Spectroscopic followup of the radio identified SMGs shows a redshift distribution between $z \sim 1.5$ –3.5 and that the SMGs dominate the total star formation in this redshift range (Chapman et al. 2003a, 2005). The recent advent of the Submillimeter Array (SMA; Ho et al. 2004) further helps to identify the radio-faint SMGs, and the redshift distribution has been extended to $z > 4$ (Iono et al. 2006;

Wang et al. 2007; Younger et al. 2007; Cowie et al. 2009; Younger et al. 2009). In addition to the redshift identifications, detailed followup observations have been made to study the properties of the SMGs in the X-ray, near-infrared, mid-infrared, and molecular line transitions (e.g., Alexander et al. 2003a, hereafter A03; Swinbank et al. 2004; Pope et al. 2008; Yun et al. 2008; Greve et al. 2005; Tacconi et al. 2006).

The followup studies of SMGs have been overwhelmingly focused on the brighter sources ($S_{850 \mu\text{m}} \gtrsim 5$ mJy), which can be easily detected by single-dish telescopes. The nature of fainter SMGs that comprise the bulk of the submillimeter background has been much less explored. Surveys of lensing cluster fields yield small samples of sub-mJy sources (Blain et al. 1999; Cowie, Barger, & Kneib 2002; Knudsen, van der Werf, & Kneib 2008). The number counts indicate that the background is dominated by sources with $S_{850 \mu\text{m}} \sim 1$ mJy and that the full resolution of the background requires detections of ~ 0.1 mJy sources. Stacking analyses statistically detect faint SMGs at 500 μ m to 1.2 mm, and various attempts have been made to study the redshift distribution of these faint SMGs (e.g., Wang et al. 2006; Serjeant et al. 2008; Marsden et al. 2009; Penner et al. 2010). However, the results from these stacking analyses have not converged to a consistent picture. A full understanding of the submillimeter background population will likely require next-generation interferometers, such as the Atacama Large Millimeter/Submillimeter Array (ALMA).

Fortunately, it is now possible to detect more typical submillimeter sources with the SMA. The recent upgrade of the SMA to a 4 GHz bandwidth not only greatly boosts its continuum sensitivity, but it also makes the calibrations with fainter quasars easier than before. This provides a first glance of what we may find in deep ALMA surveys and what issues may be present in current studies of SMGs. In this

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letter we report new SMA 340 GHz continuum observations of two SMGs, GOODS 850-11 and GOODS 850-13 (Wang, Cowie, & Barger 2004, hereafter W04), aka. GN12 and GN21 (Pope et al. 2005) in the Great Observatories Origins Deep Survey-North (GOODS-N; Giavalisco et al. 2004). Interestingly, both single-dish sources are resolved by the SMA into multiple physically unrelated galaxies. To our knowledge, these are the first examples of resolved, unrelated, multiple sources in the SMG population.

2. OBSERVATIONS AND DATA REDUCTION

The SMA observations of GOODS 850-11 and 13 were carried out on 2009 December 30 and 31, respectively. Seven of the eight SMA antennas were available in the compact configuration. Two sidebands of 4 GHz each were centered at 334 and 346 GHz. Titan was observed to provide flux calibration. The bright radio source 3C 273 was observed to provide passband calibration. Quasars 0958+655 and 1642+689, which are 17.4 and 25.1 degree from GOODS-N, respectively, were observed every 15 minutes for complex gain calibrations. The 225 GHz opacity was excellent, ~ 0.04 – 0.05 the first night and ~ 0.05 – 0.07 the second night. The averaged single-sideband system temperature was 380 K on both nights. The effective integration was ~ 4.8 and 7.2 hour per antenna on GOODS 850-11 and 13, respectively.

The calibration and data inspection were performed with the IDL-based Caltech package MIR modified for the SMA. Continuum data were generated by averaging the spectral channels after the passband phase calibration. Both gain calibrators were used to derive gain curves. However, we compared the results made with just adopting one calibrator for consistency checks, and we did not find a systematic difference. Flux calibrations were performed using data taken under conditions (time, hour angle, and elevation) similar to that of the flux calibrator. The flux calibration error is typically within $\sim 10\%$ with this method.

The calibrated interferometric visibility data were exported to the package MIRIAD for subsequent imaging and analysis. The visibility data were weighted inversely proportional to the system temperature and Fourier transformed to form images. The “robust weighting” of Briggs (1995) was also applied, with a robust parameter of 1.0, to obtain a better balance between beam size and S/N. The images were CLEANed around detected sources to approximately $1.5\times$ the noise level to remove the effects of the sidelobes. The noises measured from the CLEANed images are 0.72 and 0.68 mJy for the images of GOODS 850-11 and 13, respectively. The synthesized beams are $2''.8 \times 2''.0$ and $2''.3 \times 2''.0$ in the images of GOODS 850-11 and 13, respectively. The images were corrected for the SMA primary beam response. All our fluxes and flux errors are primary beam corrected. Source positions and fluxes were measured by fitting the image with point-source models using the MIRIAD `IMFIT` routine.

3. RESULTS

We present the SMA and multiwavelength images of GOODS 850-11 and 13 in Figures 1 and 2, their SMA astrometry, long-waveband fluxes, infrared luminosities, and redshifts in Table 1, and their optical to near-infrared spectral energy distributions (SEDs) in Figure 3. The 1.4 GHz and 24 μ m fluxes in Table 1 are adopted from Morrison et al. (2010) and the GOODS Spitzer Legacy Program DR2+ (M. Dickinson et al., in preparation), respectively, if the sources are detected. We carried out our own measurements for

weakly detected sources. Below we describe the results.

3.1. GOODS 850-11

GOODS 850-11 is known to be located in a region crowded with radio and X-ray sources (W04). The SMA detected two sources, GOODS 850-11a and 11b (see Figure 1), at significance levels of 5.6 and 4.6 σ , respectively. In W04 we found a SCUBA point-source flux of $S_{850\ \mu\text{m}} = 10.8$ mJy and a total flux of 12.7 mJy in a $30''$ region. The sum of the SMA fluxes (Table 1) of the two sources is consistent with our SCUBA measurements. Pope et al. (2006, hereafter P06) found an 850 μ m SCUBA flux of 8.6 mJy, and they considered GOODS 850-11a as an unambiguous identification (see also Greve et al. 2008; Chapin et al. 2009). A03 also considered this source to be the X-ray counterpart of the SCUBA source. Our SMA measurements show that this identification only accounts for $\sim 50\%$ of the SCUBA flux in this region. The brightest 24 μ m source in this field (a blue ACS galaxy) is also detected in the radio and X-ray, but not in the submillimeter. It is at $z = 2.004$ and is consistent with an AGN with warm dust.

GOODS 850-11a—The source is detected at 1.4 GHz by the latest Very Large Array (VLA) imaging (Morrison et al. 2010). It is also detected in the 2 Ms *Chandra* image (source number 239 in Alexander et al. 2003b). Because it is severely blended with nearby sources in the MIPS 24 μ m image, its 24 μ m flux is highly uncertain. It does not have a spectroscopic redshift from our redshift survey (Barger, Cowie, & Wang 2008). To estimate its redshift, we carried out photometric redshift fitting using the EAZY package (Brammer, van Dokkum, & Coppi 2008). We adopted the *U*-band flux from Capak et al. (2004), the ACS fluxes from the GOODS v2.0 catalog, the *J*-band flux from a deep CFHT image that we will describe elsewhere, the *HST* WFC3 F140W flux from A. Barger et al. (2010, in prep), and the K_s to IRAC fluxes from Wang et al. (2010). We adopted the default set of SED templates of Blanton & Roweis (2007) plus a dusty starburst model ($t = 50$ Myr, $A_V = 2.75$), all of which are provided in the EAZY package (see Brammer et al. (2008) for more details). These templates all include certain amounts of reddening, and we further reddened them by $A_V = 0, 0.5$, and 1.0 with the extinction law of Calzetti et al. (2000) to account for very dusty sources. We allowed for any combinations of the above templates in the fitting. The photometric redshift result for GOODS 850-11a is $z = 3.11$, and the best-fit SED is presented in Figure 3. This redshift agrees with the photometric redshift in P06, which is 3.1.

GOODS 850-11b—The source is detected by the VLA at 1.4 GHz but not by the 2 Ms *Chandra* imaging. Similar to GOODS 850-11a, it is severely blended with nearby sources in the MIPS 24 μ m image, and thus its 24 μ m flux is highly uncertain. It has a spectroscopic redshift of 2.095 (Reddy et al. 2006).

3.2. GOODS 850-13

The SMA detected three components, GOODS 850-13a, 13b, and 13c, at significance levels of 3.7, 5.5, and 5.5 σ , respectively. The significance level of GOODS 850-13a may not sound particularly high. In a $36''$ SMA primary beam FWHM, there are, on average, ~ 18 3.6 μ m sources and ~ 250 synthesized beams. For Gaussian noise, the probability of finding a $+3.7\ \sigma$ noise peak at the location of a 3.6 μ m source is the associated Gaussian probability times $18/250$,

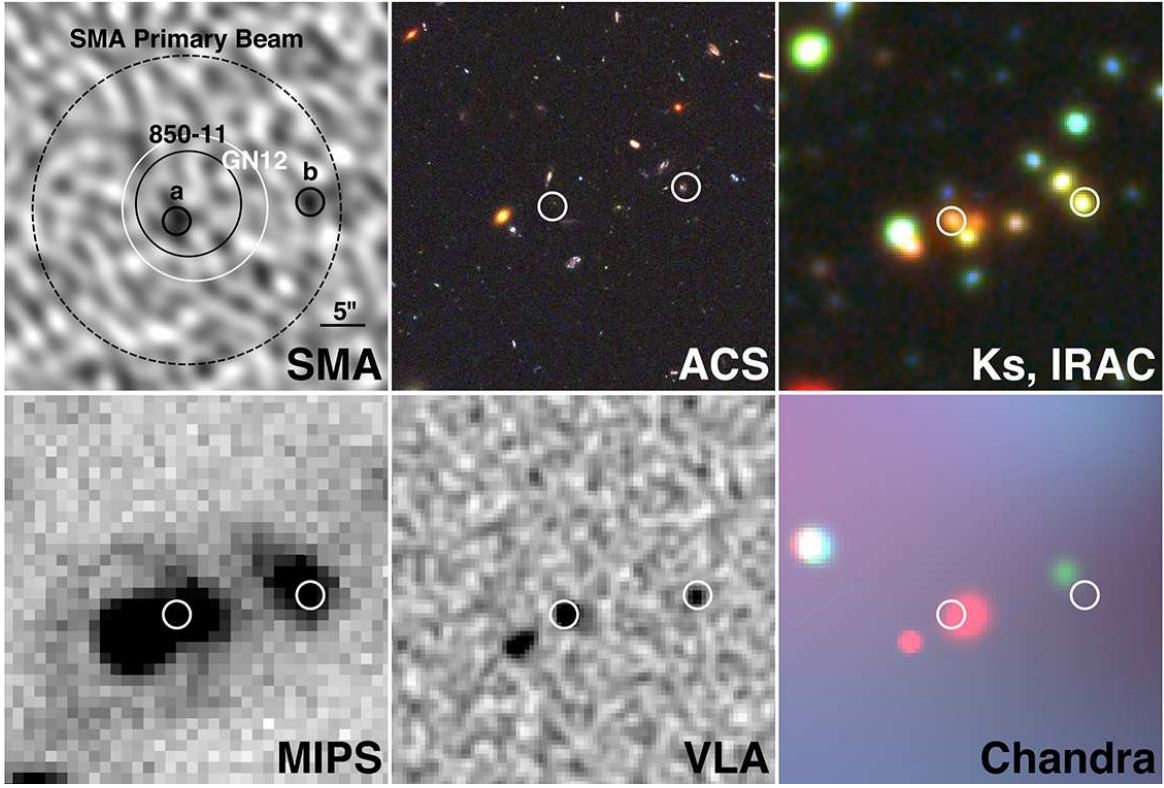


FIG. 1.— Ultradeep multiwavelength images of GOODS 850-11. A false-color optical panel is made with *HST* ACS F435W (blue), F606W (green), and F775W+F850LP (red) images. A false-color infrared panel is made with CFHT K_S (blue; Wang et al. 2010), IRAC 3.6+4.5 μm (green), and IRAC 5.8+8.0 μm (red) images. A false-color X-ray panel is made with adaptively smoothed *Chandra* 4–8 keV (blue), 2–8 keV (green), and 0.5–2.0 keV (red) images (Alexander et al. 2003b). The MIPS 24 μm image is from the *Spitzer* GOODS Legacy Program and the VLA 1.4 GHz image is from Morrison et al. (2010). For visually uniform noise, the presented SMA image is uncorrected for the primary beam, which is shown with the very large dashed circles. Large solid circles show various SCUBA positions and the associated positional uncertainties determined by W04 (black) and Pope et al. (2005; white). Small solid circles ($r = 1''.5$) in all panels indicate the SMA sources centered at the SMA positions. All grayscale images have inverted scales. North is up.

TABLE 1
BASIC PROPERTIES OF THE SMA SOURCES

ID	R.A. (J2000.0)	Dec. (J2000.0)	$S_{340\text{ GHz}}$ (mJy)	$S_{24\text{ }\mu\text{m}}$ (mJy)	$S_{1.4\text{ GHz}}$ (μJy)	L_{IR}^a (L_\odot)	z^b
GOODS 850-11a	189.19137	62.24717	4.18 ± 0.75	blended	109.6 ± 5.3	7.9×10^{12}	3.11 (2.76, 3.64)
GOODS 850-11b	189.18324	62.24741	5.27 ± 1.14	blended	32.6 ± 7.3	1.0×10^{13}	2.095
GOODS 850-13a	189.30845	62.19900	3.21 ± 0.87	93 ± 7	18.0 ± 5.3	6.1×10^{12}	3.46 (2.60, 4.50)
GOODS 850-13b	189.30944	62.20224	4.08 ± 0.75	216 ± 7	15.3 ± 4.6	7.8×10^{12}	3.157
GOODS 850-13c	189.30002	62.20341	5.34 ± 0.97	52 ± 7	31.7 ± 4.3	1.0×10^{13}	2.914

^a Infrared luminosity derived from the SMA flux and the well-known negative K -correction in the submillimeter. The conversion is $L_{\text{IR}} = 1.9 \times 10^{12} S_{850\mu\text{m}} L_\odot / \text{mJy}$ (e.g., Blain et al. 2002).

^b Redshifts with three significant digits are spectroscopic redshifts from Barger et al. (2008). Redshifts with two significant digits are photometric redshifts, with 99% confidence ranges in the parentheses.

which is 8×10^{-6} . Thus, the coincidence with the 3.6 μm source makes this detection much more secure. We therefore conclude that GOODS 850-13a is a real detection.

In W04 we noticed an elongated morphology in our SCUBA image, and our source extraction assigned the flux to two sources: GOODS 850-13 with $S_{850\text{ }\mu\text{m}} = 7.0$ mJy and 850-23 with $S_{850\text{ }\mu\text{m}} = 5.5$ mJy. The combined flux of the three SMA sources agrees excellently with the combined flux of the two SCUBA sources. P06 adopted a different source extraction in their SCUBA image and extracted only one source. They measured $S_{850\text{ }\mu\text{m}} = 5.7$ mJy, for which they identified GOODS 850-13a as the counterpart. Since then, 13a has been accepted as the counterpart in the literature (e.g., Greve et al. 2008). As was the case for GOODS 850-11, P06's identi-

cation is only partly correct and can only account for $\sim 1/4$ of the flux in this region. GOODS 850-13c was earlier considered to be the X-ray counterpart of the SCUBA source by A03 (see also Chapman et al. 2005). This identification did not agree with that in P06. Our result shows that both previous identifications are only partially correct. Even if we include both P06's (13a) and A03's (13c) identifications, we still do not have a full picture.

GOODS 850-13a—This source is detected by MIPS at 24 μm but not by the 2 Ms *Chandra* imaging. It shows a hint of weak radio emission in the VLA 1.4 GHz image of Morrison et al. (2010). We measured its 1.4 GHz flux in the VLA image with Gaussian fitting in the AIPS IMFIT routine. Ideally one would like to measure the radio flux at the best-fit

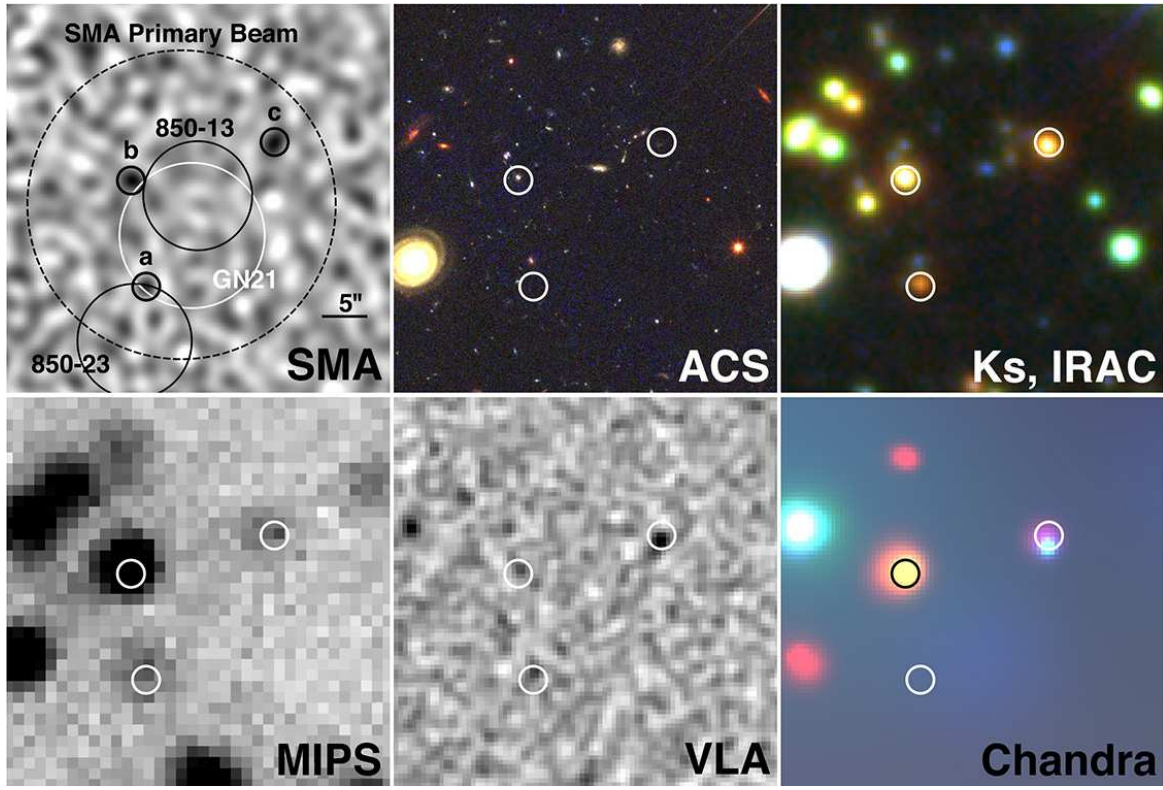


FIG. 2.— Same as Figure 1, but for GOODS 850-13.

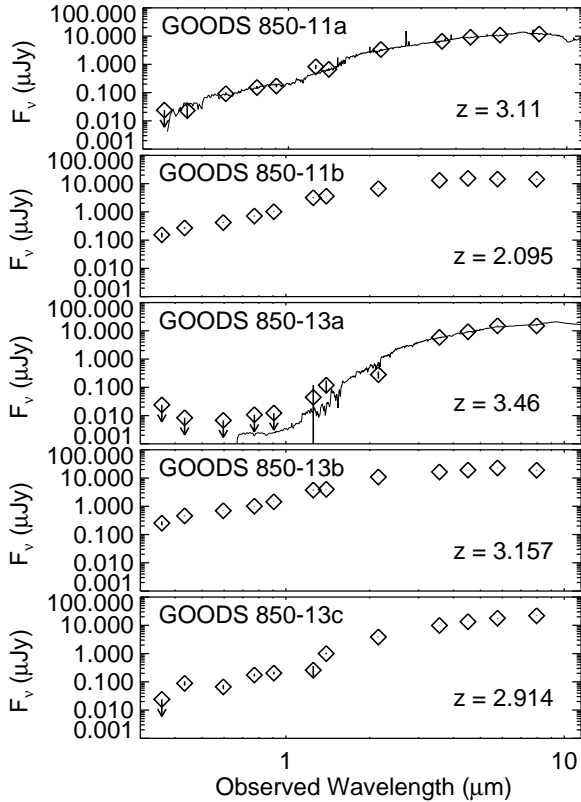


FIG. 3.— Optical and infrared SEDs of the SMA sources. Symbols show observed SEDs. Best-fit SEDs for sources without spectroscopic redshifts are plotted with curves, and the corresponding redshifts are the fitted photometric redshifts.

SMA position. However, given the relatively low SMA S/N and therefore the larger positional uncertainty, we decided to measure the radio flux at the local radio peak. The result (Table 1) may be biased by positive noise spikes and therefore should only be considered as an upper limit.

GOODS 850-13a is extremely optically faint (undetected by ACS, Figures 2 and 3), and it does not have a spectroscopic redshift. Its photometric redshift (based on photometry in the K_S and IRAC bands) is 3.46. This redshift is very similar to the spectroscopic redshifts of 13b and 13c, so we cannot rule out a physical association between 13a and one of the other two.

GOODS 850-13b—This source is bright at $24\ \mu\text{m}$ but quite faint in the radio. We measured its 1.4 GHz flux (Table 1) in the same way as for GOODS 850-13a, so it should be considered as an upper limit. On the other hand, GOODS 850-13b is detected in the 2 Ms *Chandra* image (source number 377 in Alexander et al. 2003b), making it a new X-ray SMG that was previously unknown in the literature. It has a spectroscopic redshift of 3.157 (Barger et al. 2008).

GOODS 850-13c—This source is significantly detected by the VLA (Morrison et al. 2010) and by *Chandra* (source number 369 in Alexander et al. 2003b), but it is relatively faint at $24\ \mu\text{m}$. It has a spectroscopic redshift of 2.914 (Chapman et al. 2005).

4. DISCUSSION

Since the commissioning of the SMA, it has been used for followup observations of SMGs, either for identification (e.g., Iono et al. 2006; Wang et al. 2007; Younger et al. 2007; Cowie et al. 2009; Younger et al. 2009) or for morphology (e.g., Younger et al. 2008). This is the first time that the SMA has discovered new SMGs. The multiple SMA detections illustrate the limitations of identifying SMGs in any wavelength

other than the submillimeter itself. Both sources had radio, 24 μm , and X-ray identifications in P06 and A03. All of the previously proposed identifications are only partially correct; i.e., they are all legitimate SMGs, but the submillimeter fluxes and source numbers will be misinterpreted by up to a factor of 3. If such cases are common, then our understanding of the SMG population is fundamentally flawed.

The effects of multiple SMGs are commonly included in single-dish number counts simulations (e.g., Eales et al. 2000; Scott et al. 2002; Coppin et al. 2006; W04). However, its importance (relative to other effects such as Eddington bias) has not been directly demonstrated by observations. So far only sensitive millimeter/submillimeter interferometric observations can reveal the existence of multiple SMGs like GOODS 850-11 and 13, since existing single-dish telescopes are still severely confusion limited (at $> 850 \mu\text{m}$) or noise limited (at $450 \mu\text{m}$). The SMA surveys of Younger et al. (2007, 2009) imaged 15 SMGs selected at 1.1 mm. They did not find evidence of multiple sources, consistent with the argument made by Ivison et al. (2007) that multiple sources are rare. However, the SMA surveys of Younger et al. have 345 GHz rms sensitivities of 1–2 mJy. Even if there are secondary sources with $S_{345 \text{ GHz}} \sim 3\text{--}5$ mJy in their survey fields, such sources would not be easily detected. Our SMA survey is the first one that is deep enough to reveal such cases.

After the SMA upgraded to the 4 GHz bandwidth, we observed five GOODS-N SMGs at similar depths (A. Barger et al., in preparation). Two of them are resolved into multiple sources and reported here. There is a third resolved source that will be reported by Barger et al. It is unclear whether this source is a merger or a physically unrelated pair. Even if we exclude the third source, the frequency of multiple sources in our SMA sample still seems unusually high. To better understand this, we performed Monte Carlo simulations that mimic our SCUBA and SMA surveys.

We first created 1000 simulated SCUBA images using the differential counts in Cowie, Barger, & Kneib (2002) and Coppin et al. (2006), the “true-noise” map created in our GOODS-N SCUBA survey in W04, and the SCUBA beam in W04. We then extracted the simulated SCUBA sources. For each SCUBA source detected at > 5 mJy and $> 4\sigma$ (the selection criteria for our SMA observations), we searched the input catalog for any > 3 mJy (our SMA detection limit) sources within $17''$ (the SMA primary beam HWHM) of the SCUBA position. In the simulations the mean number of > 5 mJy sources in a W04 SCUBA area is 11.4 ± 3.9 , where the uncertainty is the dispersion in the 1000 realizations and is nearly Poissonian. This value is consistent with the W04 SCUBA observations (15 sources). On the other hand, it is significantly larger than the cumulative count, as it is affected by blending and flux boosting. The measured counts take these effects out. The mean numbers of double and triple systems are 1.29 ± 1.33 and 0.06 ± 0.27 , respectively.

We had observed 10 of the 15 > 5 mJy SCUBA sources with the SMA. The most recent five of the 10 SMA observations were deep enough to detect > 3 mJy sources. The earlier

SMA observations were shallower, so there was a selection bias against SCUBA sources with multiple counterpart candidates. Given this bias and to be conservative, we only scale the above values of 1.29 ± 1.33 and 0.06 ± 0.27 by a factor of 10/15, rather than 5/15. We thus expect to find 0.86 ± 0.89 double and 0.04 ± 0.18 triple systems. The probability of finding one triple system like GOODS 580-13 is only 4%, inconsistent with the actual observations. Among the possible explanations, the most likely one is clustering of SMGs, which is not included in the simulations. This is plausible because the photometric redshift of GOODS 850-13a has a confidence range (Table 1) covering the redshift of 13b or 13c. This can be tested this with future spectroscopic observations in the near-infrared or in the millimeter.

In the same simulations, we increased the SMA detection limit to 4 mJy, and we found that the probability of multiple systems dramatically decreases to $\sim 6\%$. This is consistent with the SMA survey results of Younger et al. (2007, 2009). By altering the details of the simulations, we also found that the above results are fairly insensitive to the following SCUBA and SMA observing strategies: (1) the source extraction (various detection thresholds), (2) flux measurement in the SCUBA map (simple aperture flux vs. optimally filtered flux using the beam), (3) the shape of the SCUBA sidelobes (determined by the secondary chopping), and (4) the decision on where to point the SMA (as long as it is within the SCUBA positional uncertainty).

We can use our simulations to predict the early results of ALMA identifications of SCUBA sources. We adopt the primary beam HWHM of $8''.5$ of ALMA at 340 GHz. In the ALMA early science phase we expect to have at least 10 antennae, and we can detect 0.5 mJy sources in roughly one hour. If we point ALMA at a > 5 mJy SCUBA source, the probabilities of detecting double and triple SMGs within the primary beam will be 29% and 6.5%, respectively. The combined fraction of $\sim 35\%$ is very high. We therefore predict that multiple detections in early ALMA observations will be quite common.

At the beginning of this section, we raised the issue about incomplete identifications of SMGs in the X-ray, 24 μm , and radio. Based on our SMA observations and the above simulations, we believe that multiple systems and therefore incomplete identifications are common. Thus, we suggest that large numbers of single-dish sources should be re-identified with sensitive interferometric observations, even if the sources were previously thought to be securely identified.

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